

Sources of GeV Photons and the Fermi Results

Chuck Dermer (NRL)

1. GeV instrumentation and the GeV sky with the Fermi Gamma-ray Space Telescope
2. First Fermi Catalog of Gamma Ray Sources and the Fermi Pulsar Catalog
- 3. First Fermi AGN Catalog**
4. Relativistic jet physics and blazars
5. γ rays from cosmic rays in the Galaxy
- 6 γ rays from star-forming galaxies and clusters of galaxies, and the diffuse extragalactic γ -ray background
7. Microquasars, radio galaxies, and the extragalactic background light
8. Fermi Observations of Gamma Ray Bursts
9. Fermi acceleration, ultra-high energy cosmic rays, and Fermi

Thanks to B. Lott, P. Giommi, M. Ajello

First Fermi AGN Catalog

EGRET Legacy

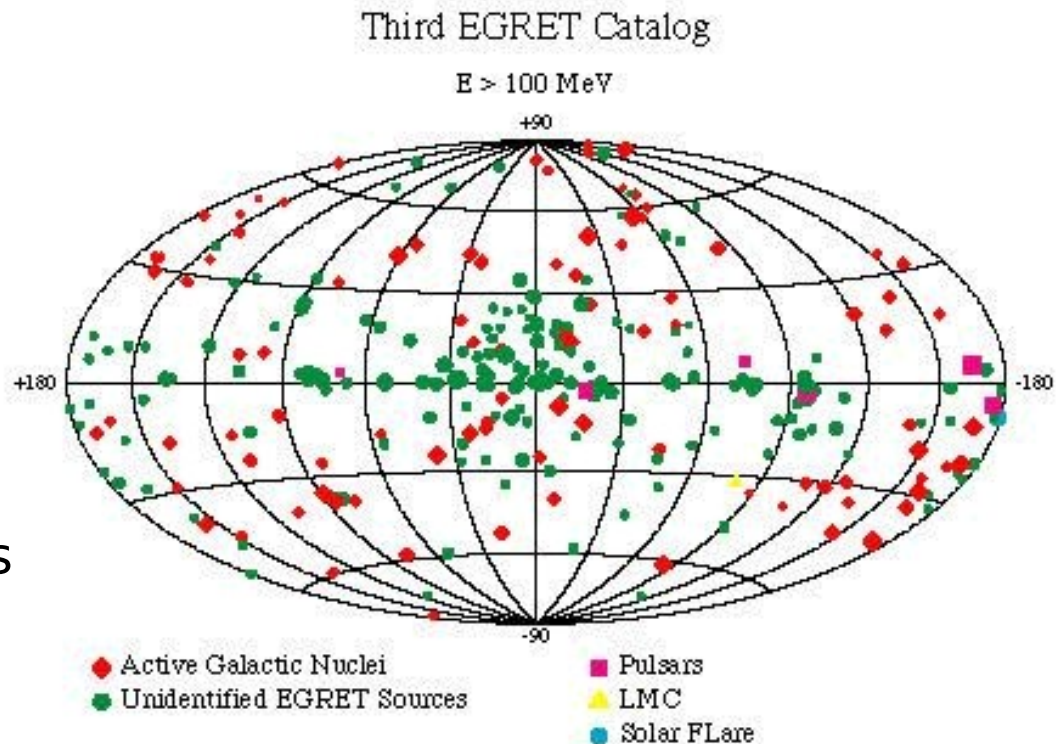
66 hi-confidence ($>5\sigma$)
sources associated with
AGNs (Hartman et al. 1999)
[31 $>10\sigma$ sources (total)
(10 at $|b|>10^\circ$)]

All 66 associated with
radio-loud AGNs—blazars
+ 1 radio galaxy

23% with BL Lac objects

77% with flat spectrum
radio quasars

$z_{\text{max}} = 2.286$



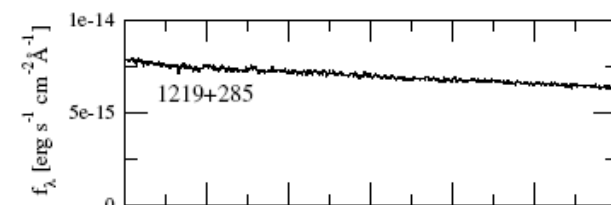
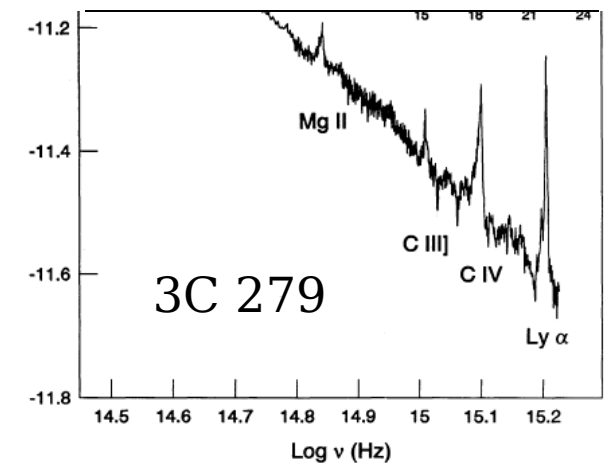
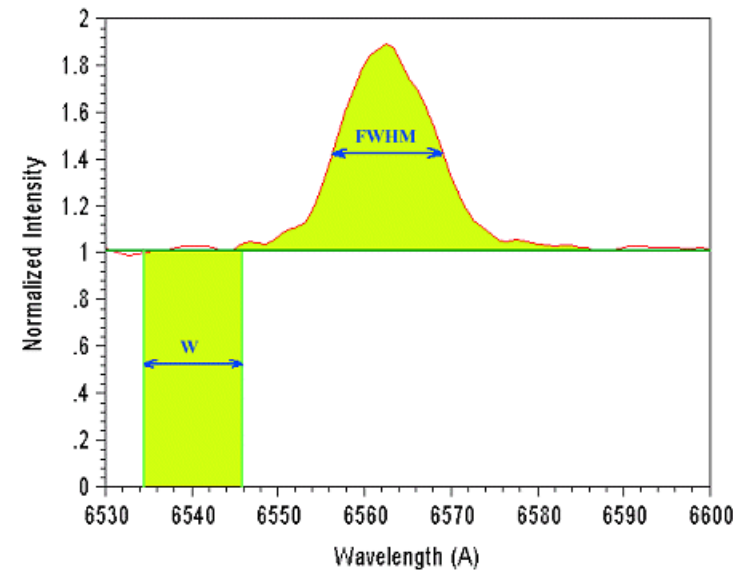
Blazars:

optically violently variable (OVV; 50% in a day)
flat radio spectrum ($\alpha_r > -0.5$ at GHz frequencies)
high optical polarization ($> \text{few } \%$)
superluminal motion

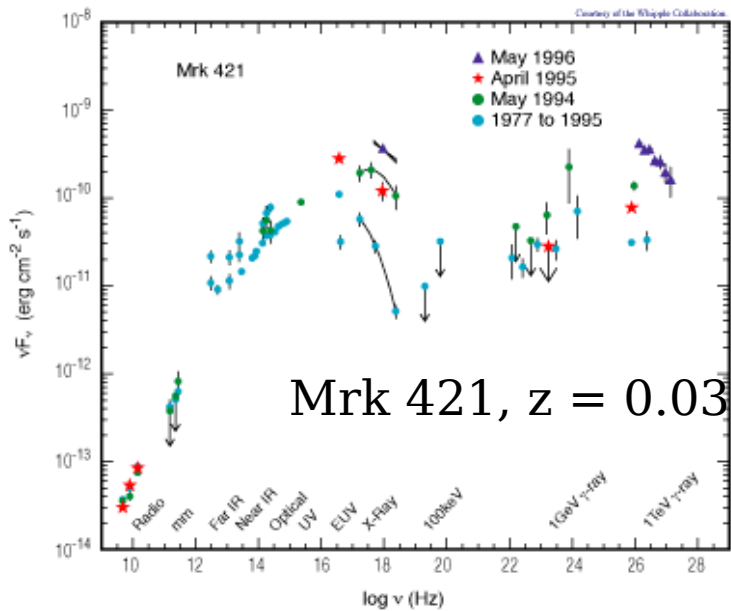
BL Lac and FSRQ: (our)

definition

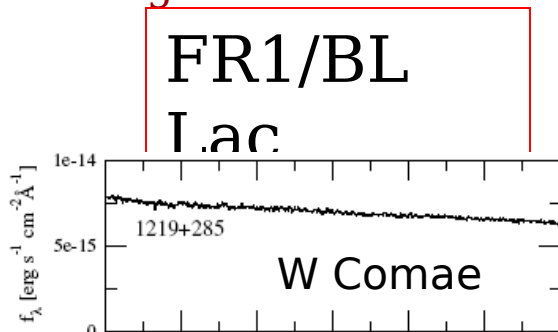
- classify an object as a BL Lac if the equivalent width (EW) of the strongest optical emission line is $< 5 \text{ \AA}$, e.g., [O II] $\lambda 3727$ and [O III] $\lambda 5007$
- classification of higher-redshift sources will preferentially use lines at shorter wavelengths (e.g., Ly α $\lambda 1216$ and C IV $\lambda 1549$) than for low-redshift sources (e.g., Mg II $\lambda 2798$ and H α $\lambda 6563$).
- a Ca II H/K break ratio $C < 0.4$,
- Wavelength coverage satisfies $(\lambda_{\text{max}} - \lambda_{\text{min}})/\lambda_{\text{max}} > 1.7$ so that at least one strong emission line would have been detected if it were present.
- Sources for which no optical spectrum or of insufficient quality to determine the optical classification are listed as “unknown type”



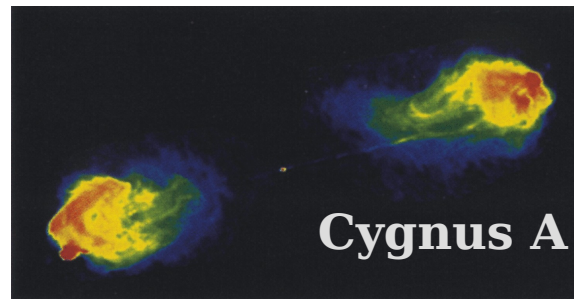
Radio Galaxies and Blazars



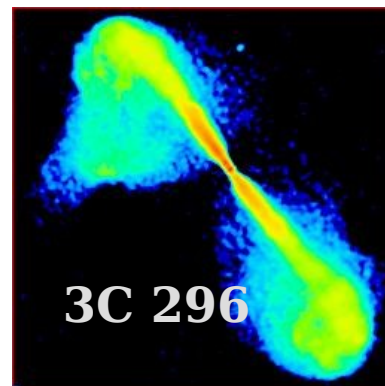
$L \sim 10^{45} \times (f/10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1})$
 erg s^{-1}



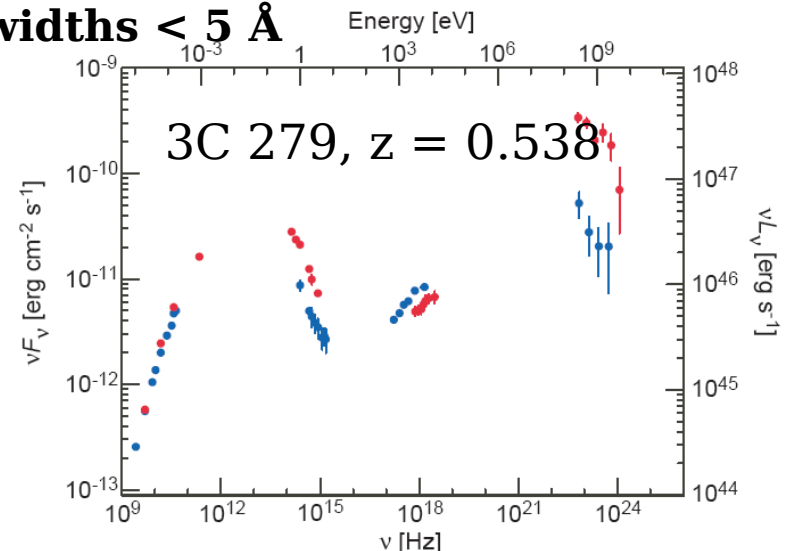
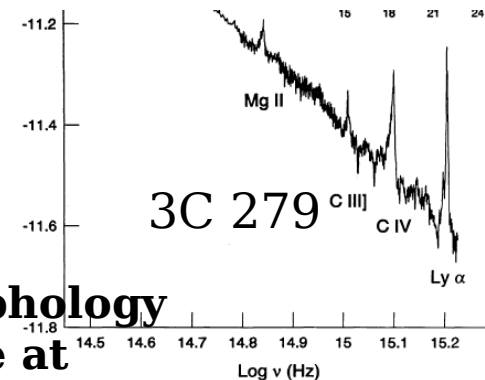
FR1/BL
 Lac



FR1/2: radio power/morphology correlation; dividing line at $\approx 10^{42} \text{ ergs s}^{-1}$ ($2 \times 10^{25} \text{ W/Hz}$ at 178 MHz)
BL Lacs: optical emission line equivalent widths $< 5 \text{ \AA}$

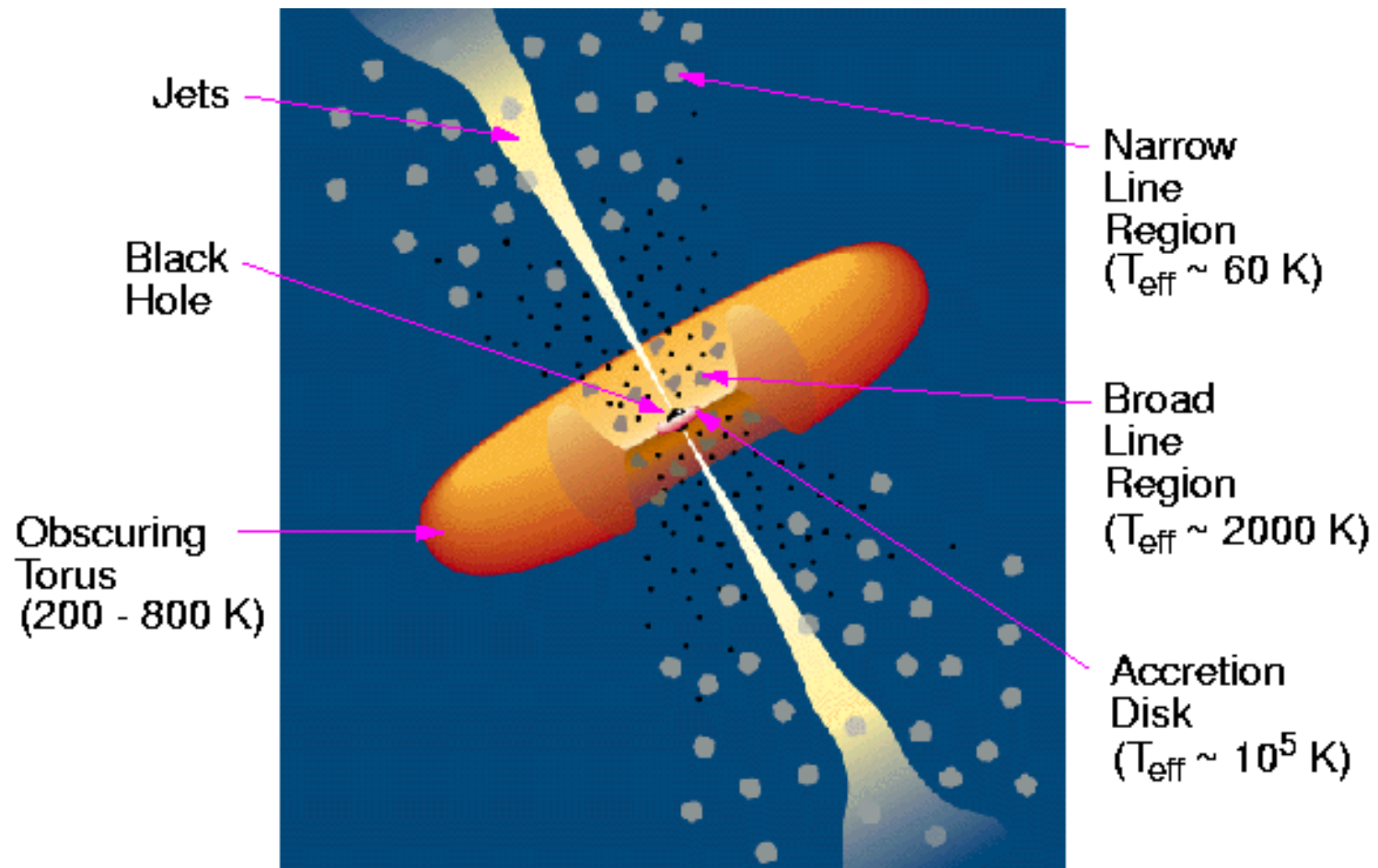


FR2/FSRQ



AGN Unification Paradigm

(Urry and Padovani 1995)



γ -Ray Blazars and Radio Galaxies

- LAT Bright AGN Sample (LBAS); First year LAT AGN Catalog (1LAC)

LBAS: 3 month source list: 2008 Aug 4 – Oct 30

1LAC: 1 year catalog: 2008 Aug 4 – 2009

LBAS: subset of 0FGL w/ 205 sources

TS >100 ($>10\sigma$)

106 $|b|>10^\circ$ sources

assoc. w/ AGNs

1FGL **TS** >25

1451 sources

1043 $|b|>10^\circ$ sources

1LAC

TS >25 ($>4.1\sigma$)

671 assoc. w/ 709 AGN

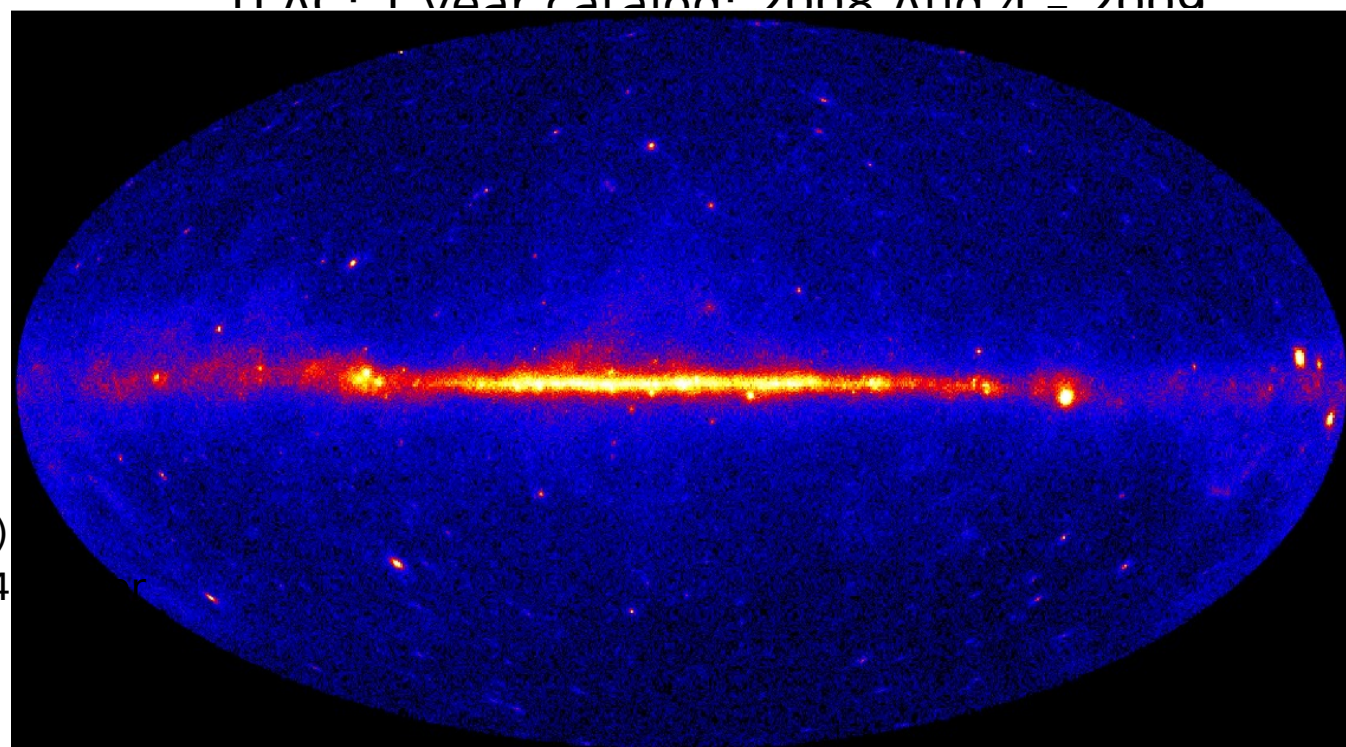
(663 hi-conf. associations)

(300 BL Lacs, 296 FSRQ, 4
AGN, 72 unknown)

3EG (EGRET):

10 $>10\sigma$ $|b|>10^\circ$ sources

66 $>5\sigma$ blazars

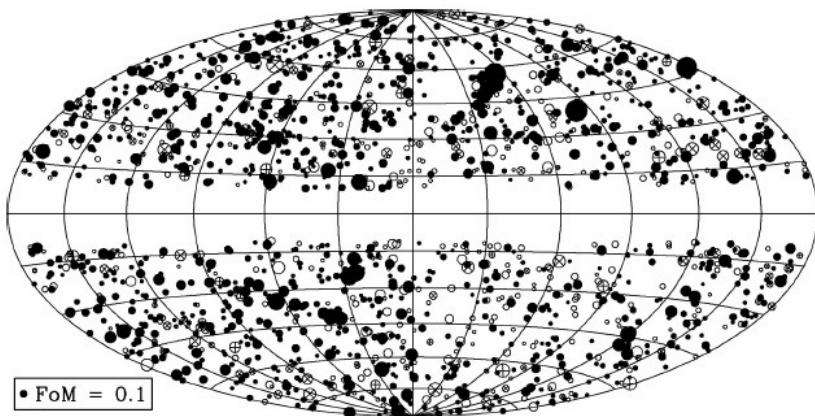


1 year Fermi GeV sky

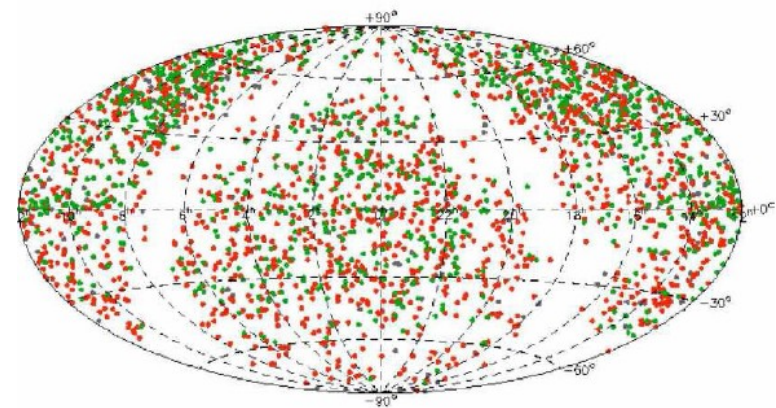
Associations (not Identifications)

- Depends primarily on spatial coincidence
- Catalogs used:
 - CRATES: Combined Radio all-Sky Targeted Eight GHz Survey
 - 11,000 $|b| > 10^\circ$ flat-spectrum with positions, 8.4 GHz flux densities, α_r
 - CGRaBS: Candidate Gamma-Ray Blazar Survey
 - 1625 CRATES sources with similar radio and X-ray properties as EGRET blazars
 - BZCAT

CGRaBS



rs/blazar-like sources BZCat EGRET



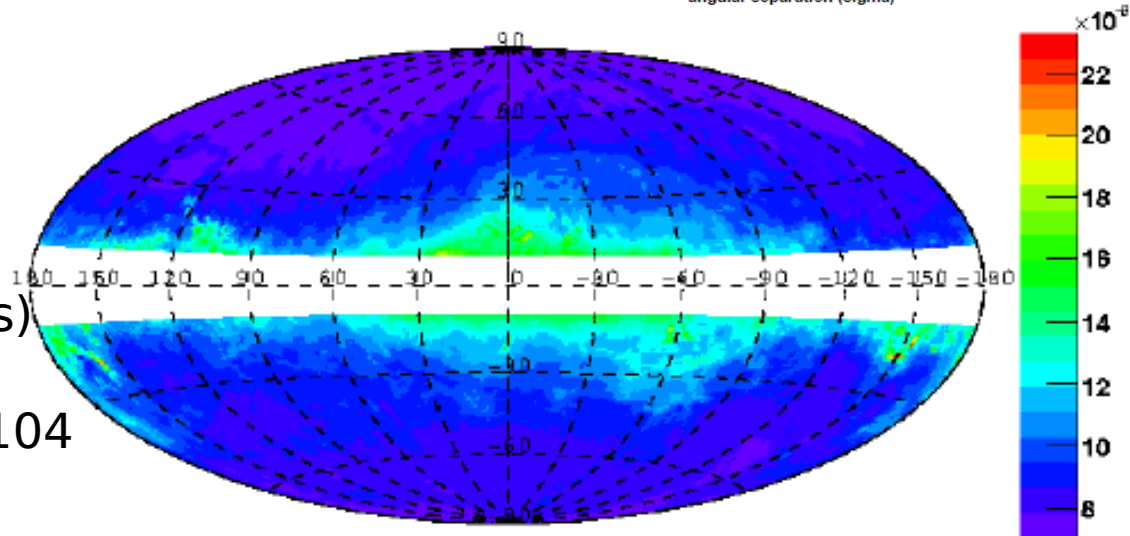
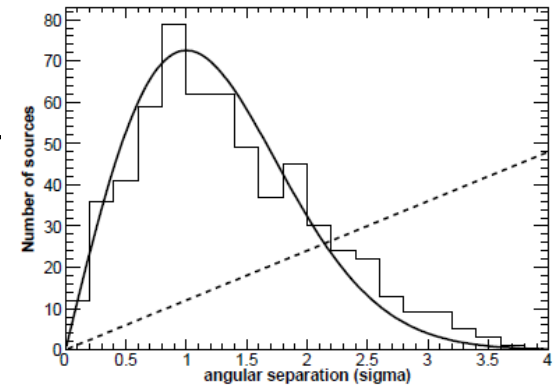
Associating AGNs in the 1LAC

- ❑ TS map using point fit
- ❑ Elliptical fits to the 95% confidence contour
 - 18 month EGRET sky survey: 0.62°
 - High-latitude 1FGL sources: 0.15°
 - LBAS source: 0.09°

- **Not complete**
- **Not flux-limited**
- **Not uniform**

- ❑ 671 assoc. w/ 709 AGN
- ❑ Clean sample of 599 AGN (expect ~ 11 false positives)
- ❑ 51 low-latitude
- ❑ 109 AGN “affiliations” for 104 high-latitude sources

Compare 5σ two-week limit for EGRET $\cong 150 \times 10^{-9}$ -- 250×10^{-9}



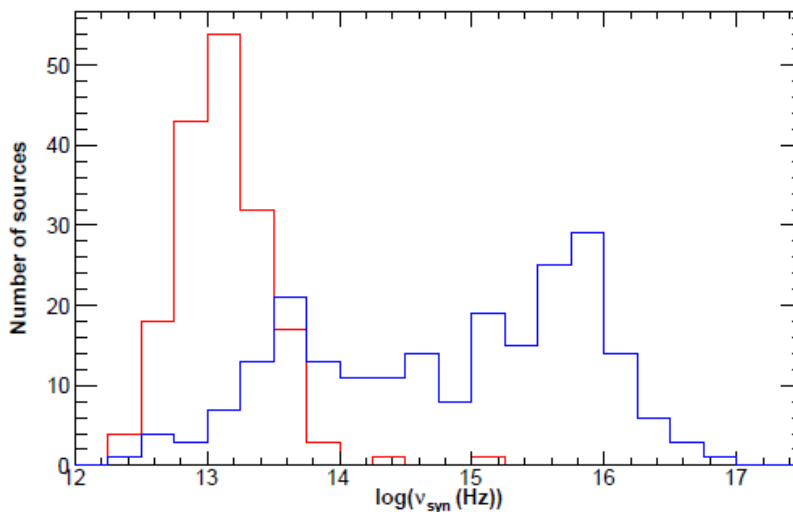
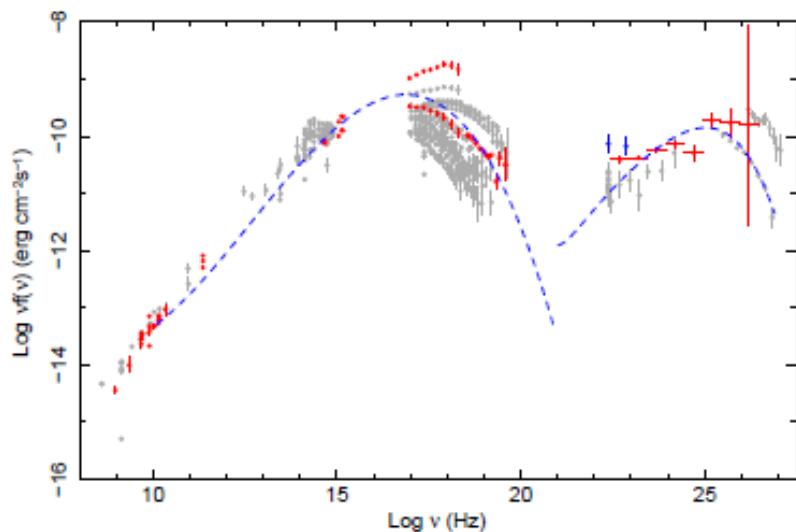
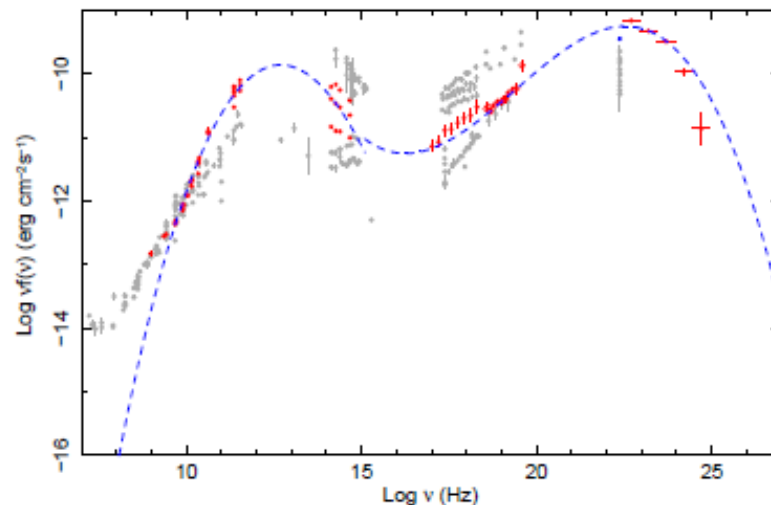
5σ Flux limit as a function of sky location,

assuming $\Gamma = 2.2$

Major Types of Fermi AGN

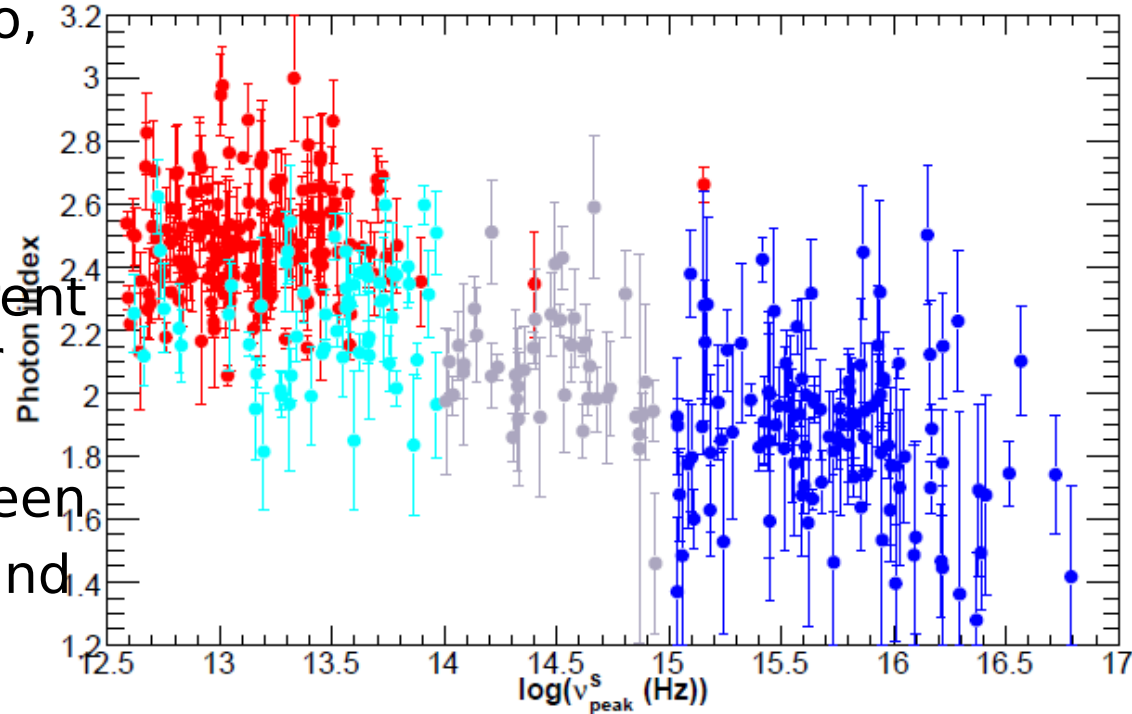
Abdo et al. 2010, Apj, 710, 1271

- ❑ FSRQs vs. BL Lacs
- ❑ LSP ($\nu_{\text{pk}}^{\text{syn}} < 10^{14}$ Hz), ISP,
HSP ($\nu_{\text{pk}}^{\text{syn}} > 10^{15}$ Hz)
- ❑ Unknown
- ❑ NLSy1 RG
- ❑ Non-blazar AGN

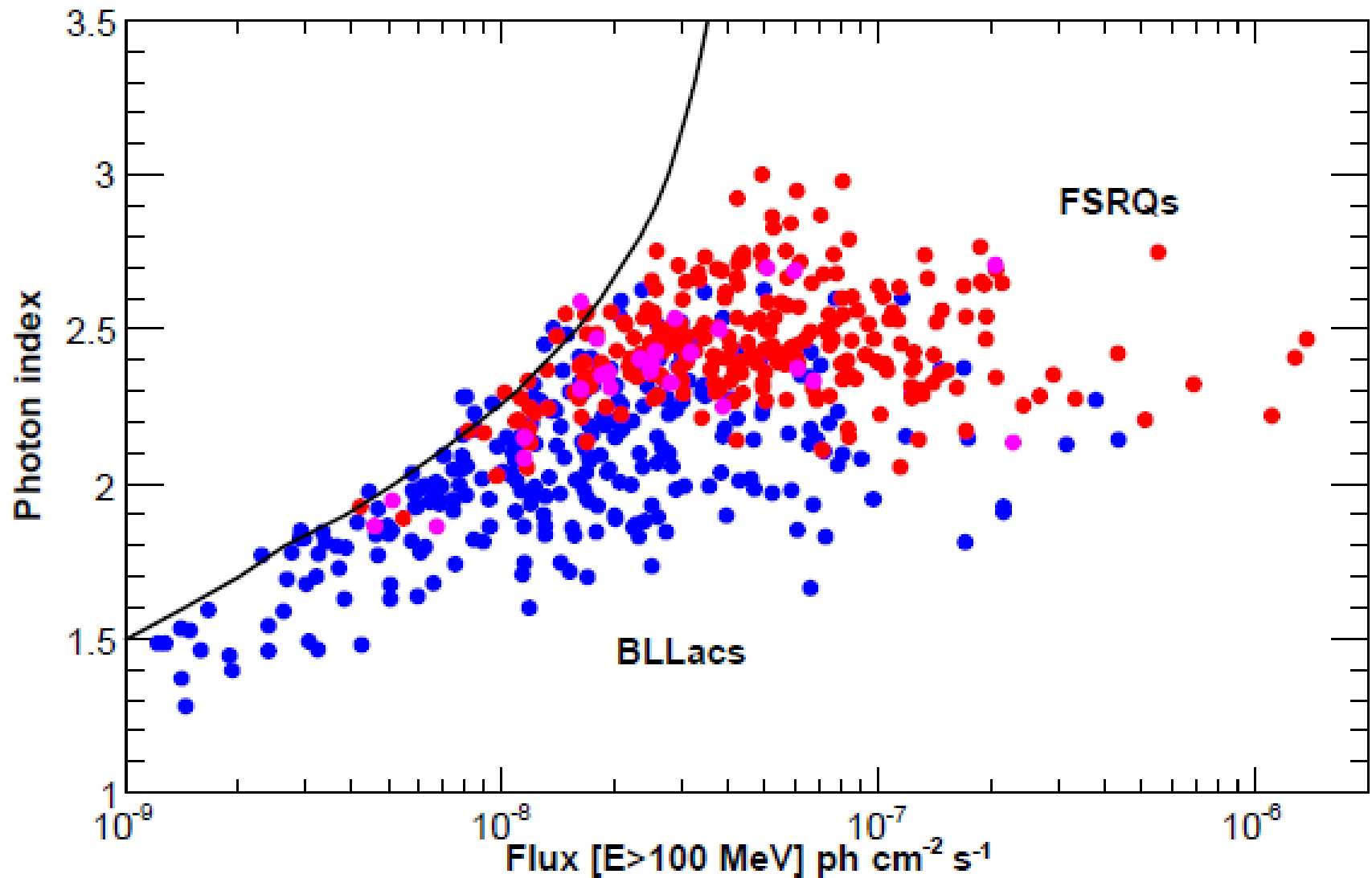


Properties of 1LAC

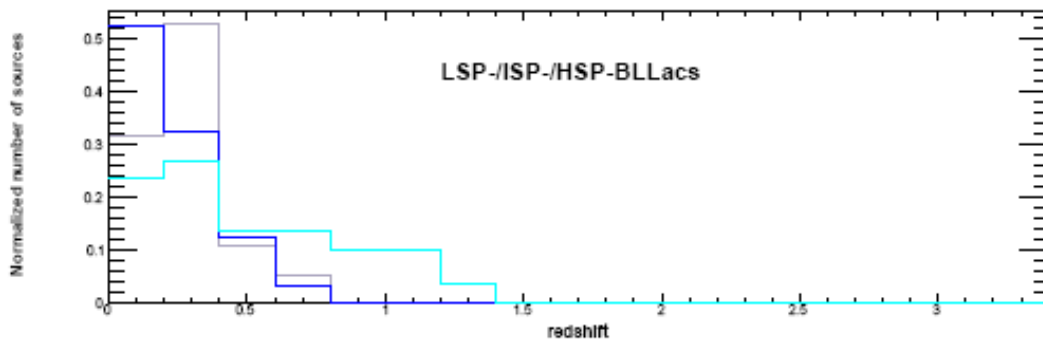
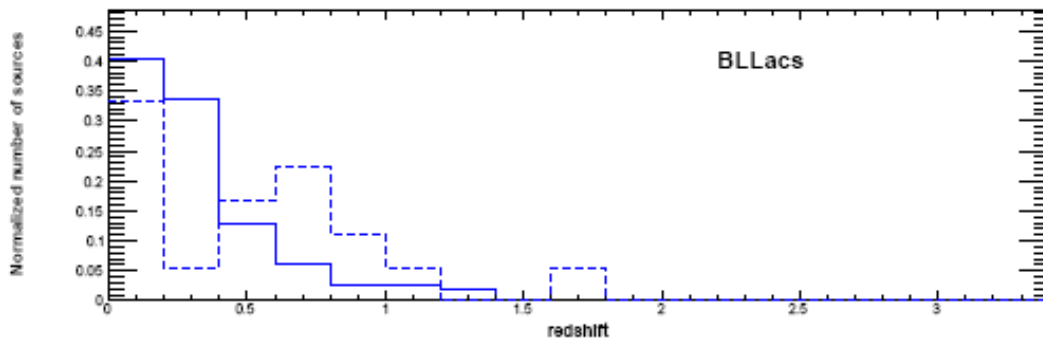
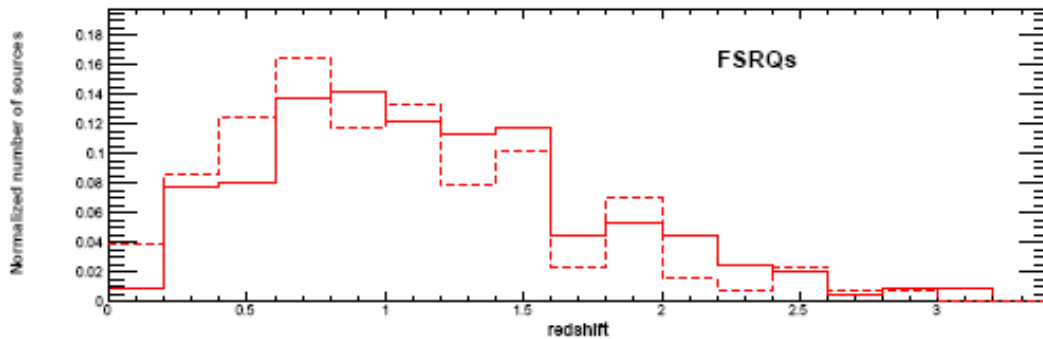
- ❑ Small number of non-blazar sources
 - 6 RG, 3 starburst (**incl. NGC 4945**), 2 SSRQs, 5 NLRGs, 10 “RQ”, other “oddballs” Redshift distributions peaking at $z \approx 1$ FSRQs, at low redshift for BL Lacs
 - **N.B.:** Only 121 out of 291 1LAC BL Lacs have measured redshifts
- ❑ A high BL Lac/FSRQ ratio, close to unity
- ❑ A high HSP/LSP ratio among BL Lacs
- ❑ Little evidence for different variability properties for FSRQs and BL Lacs
- ❑ Strong correlation between photon spectral index and blazar class



Photon Index vs. Flux



Redshift Distribution

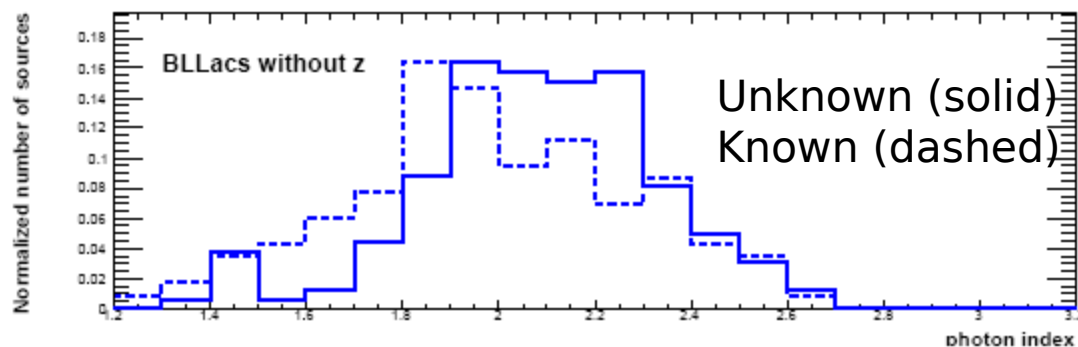
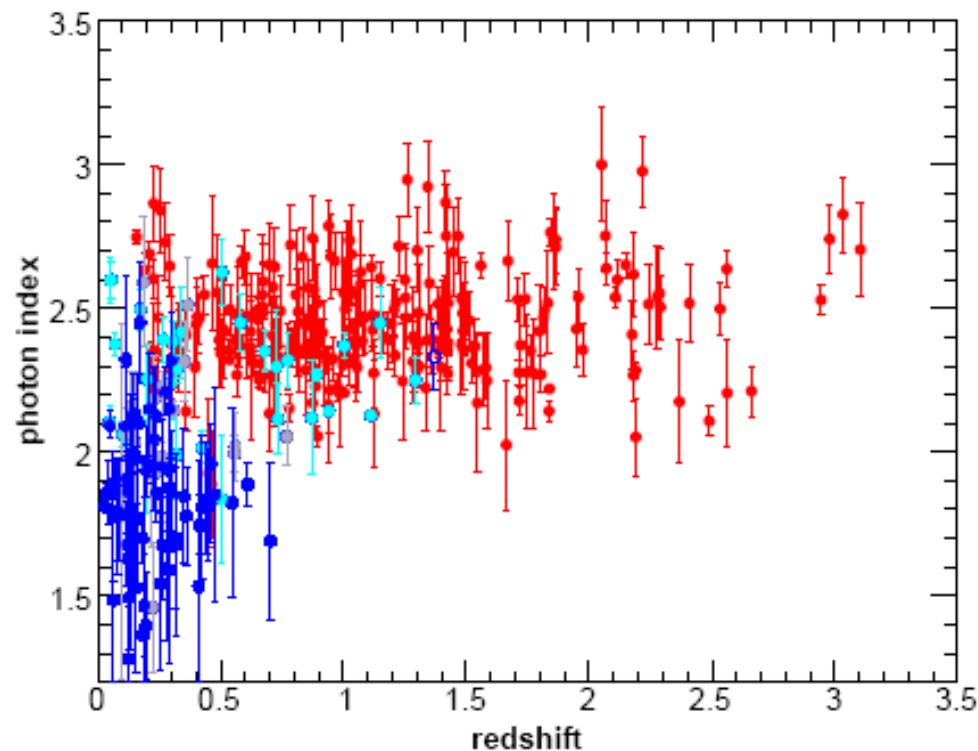


□ LBAS Redshifts
Similar to EGRET
distributions

□ Compare with
distribution of
WMAP blazars (1
Jy at 41 GHz)

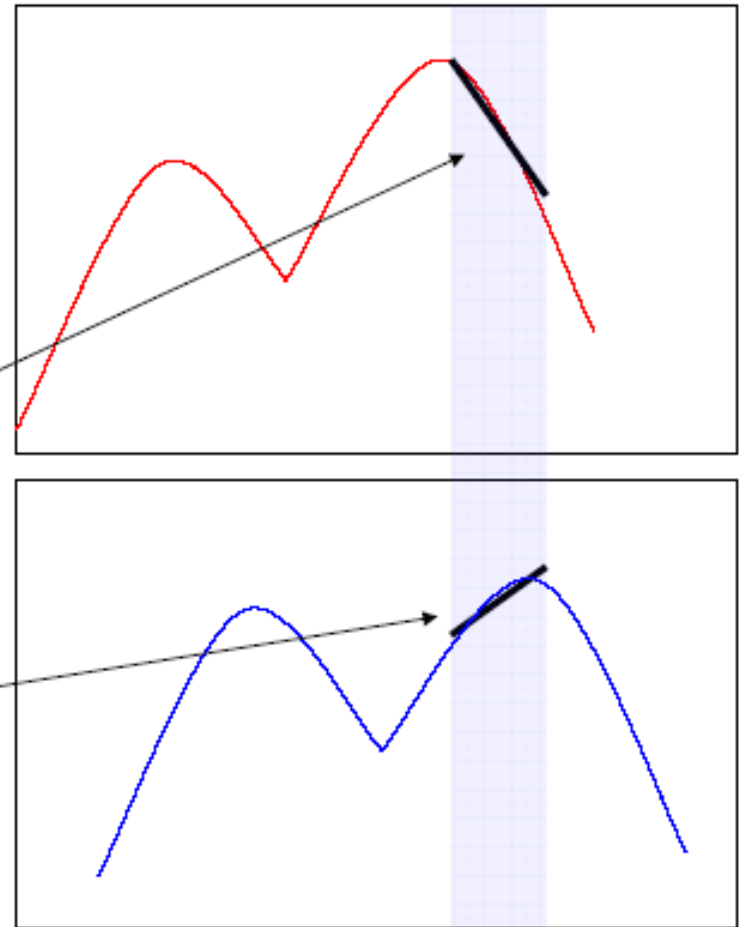
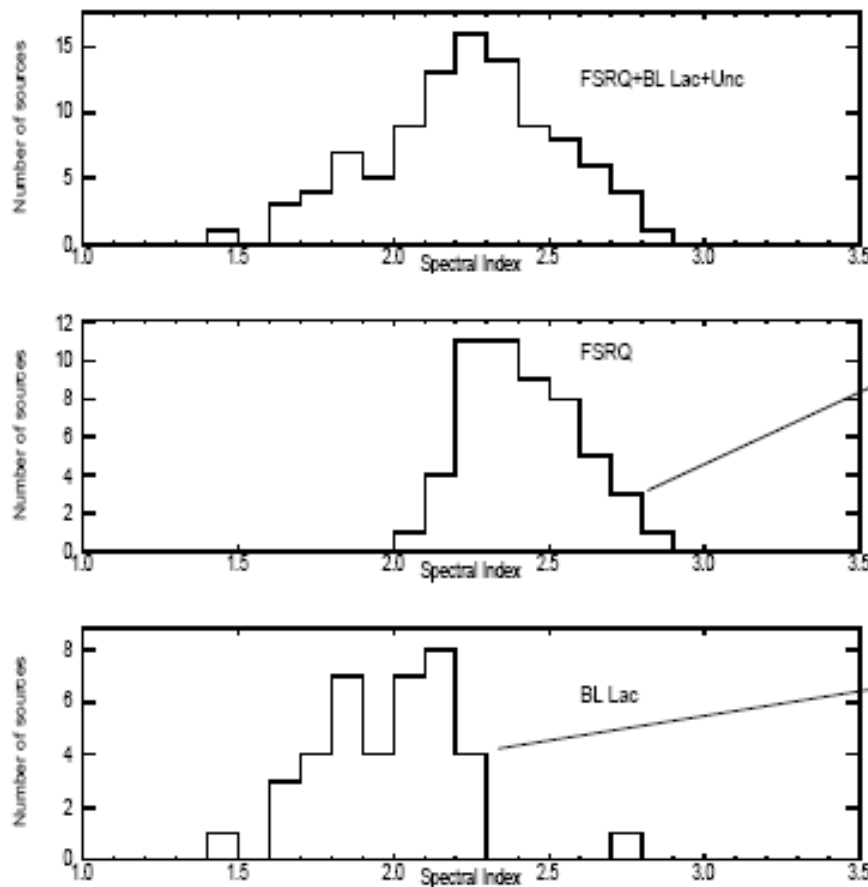
Redshift Distribution

- Red: FSRQ; cyan: LSP BL Lac; gray: ISP BL Lac; blue: LSP BL Lac; magenta: radio galaxies
- Strong selection biases to detect soft spectrum sources at given flux level
- Heavily biased against steep spectrum faint sources; therefore flat spectrum faint sources over-represented

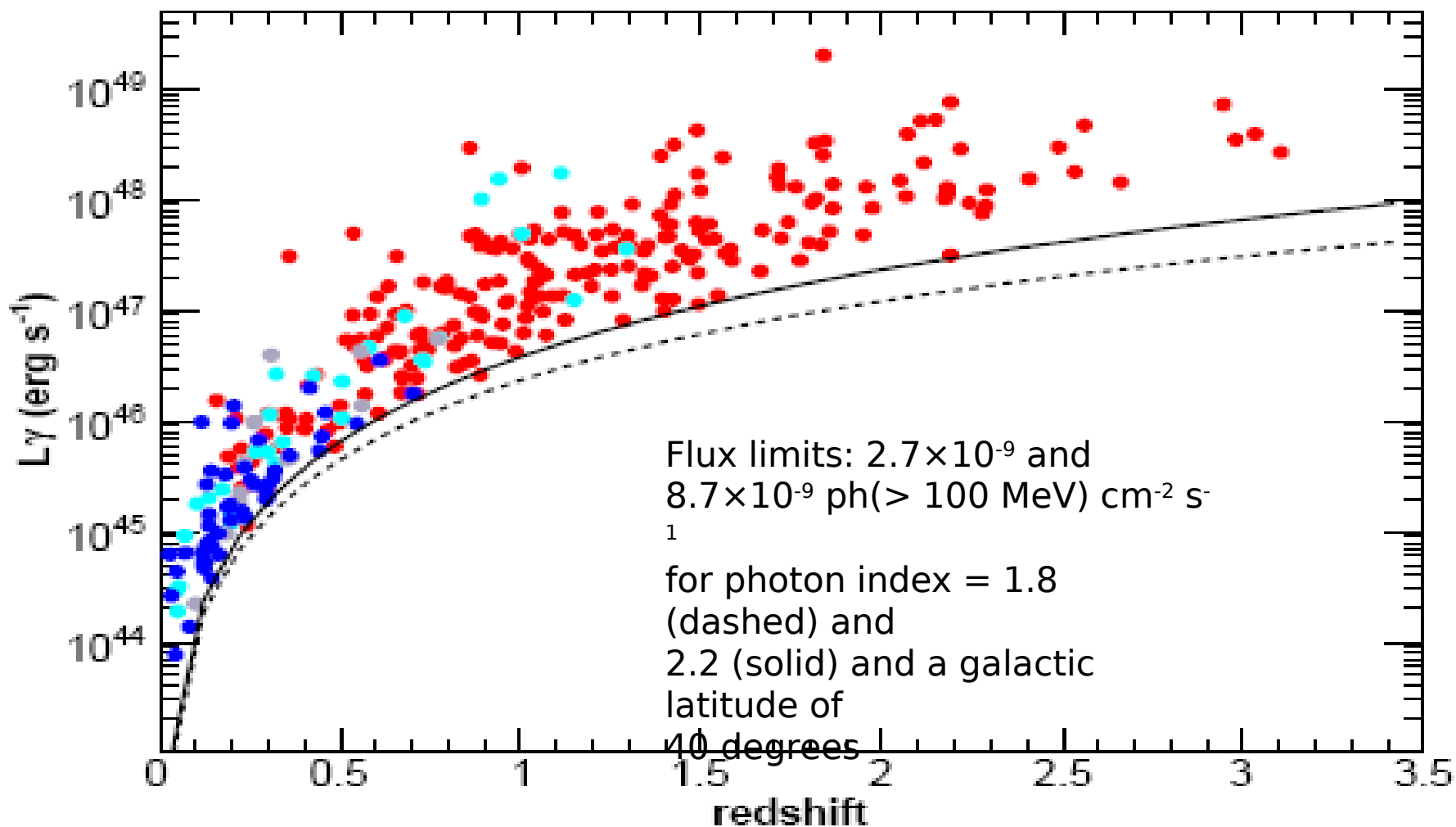


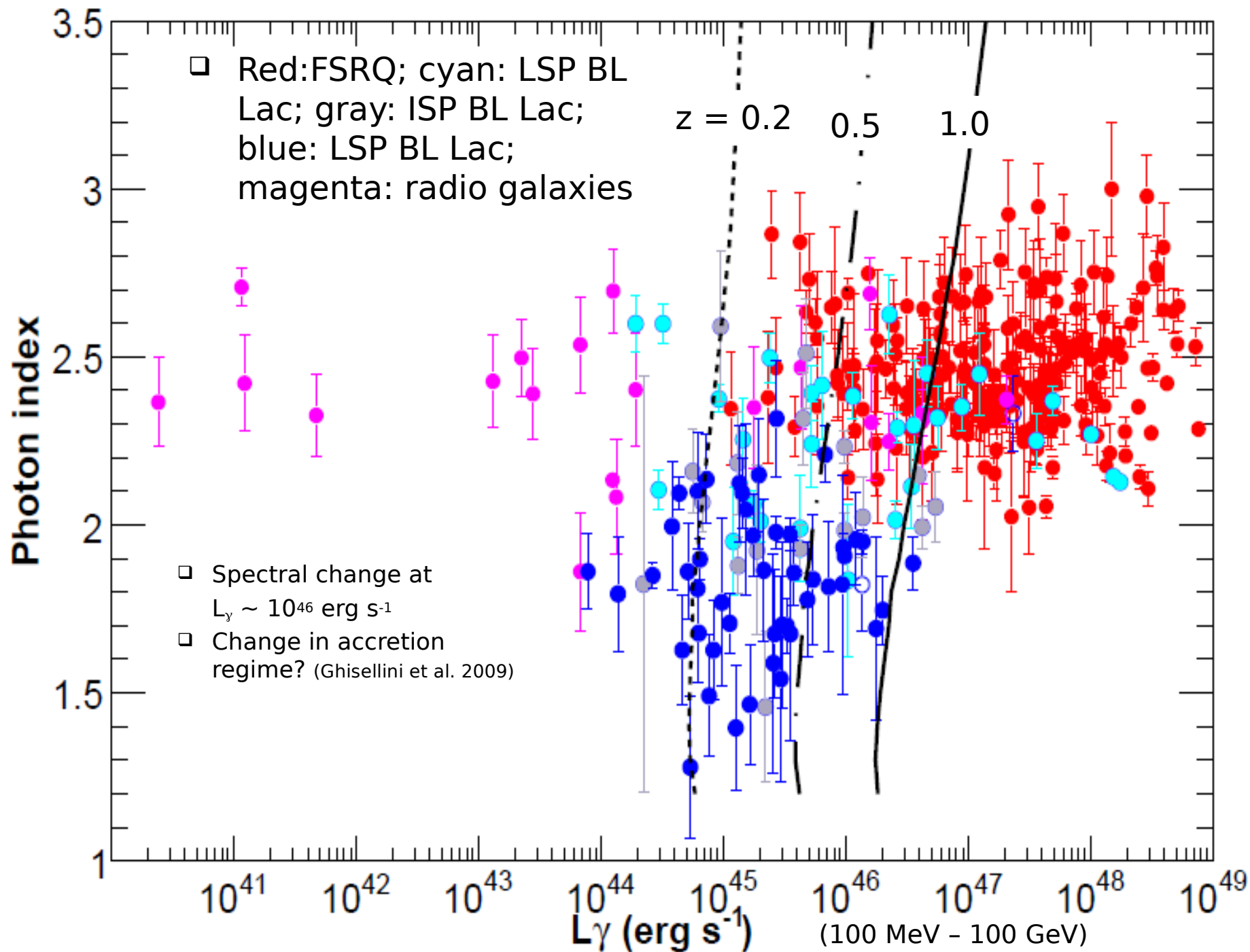
Spectral Index Distribution

- Sampling separate FSRQ and BL Lac populations



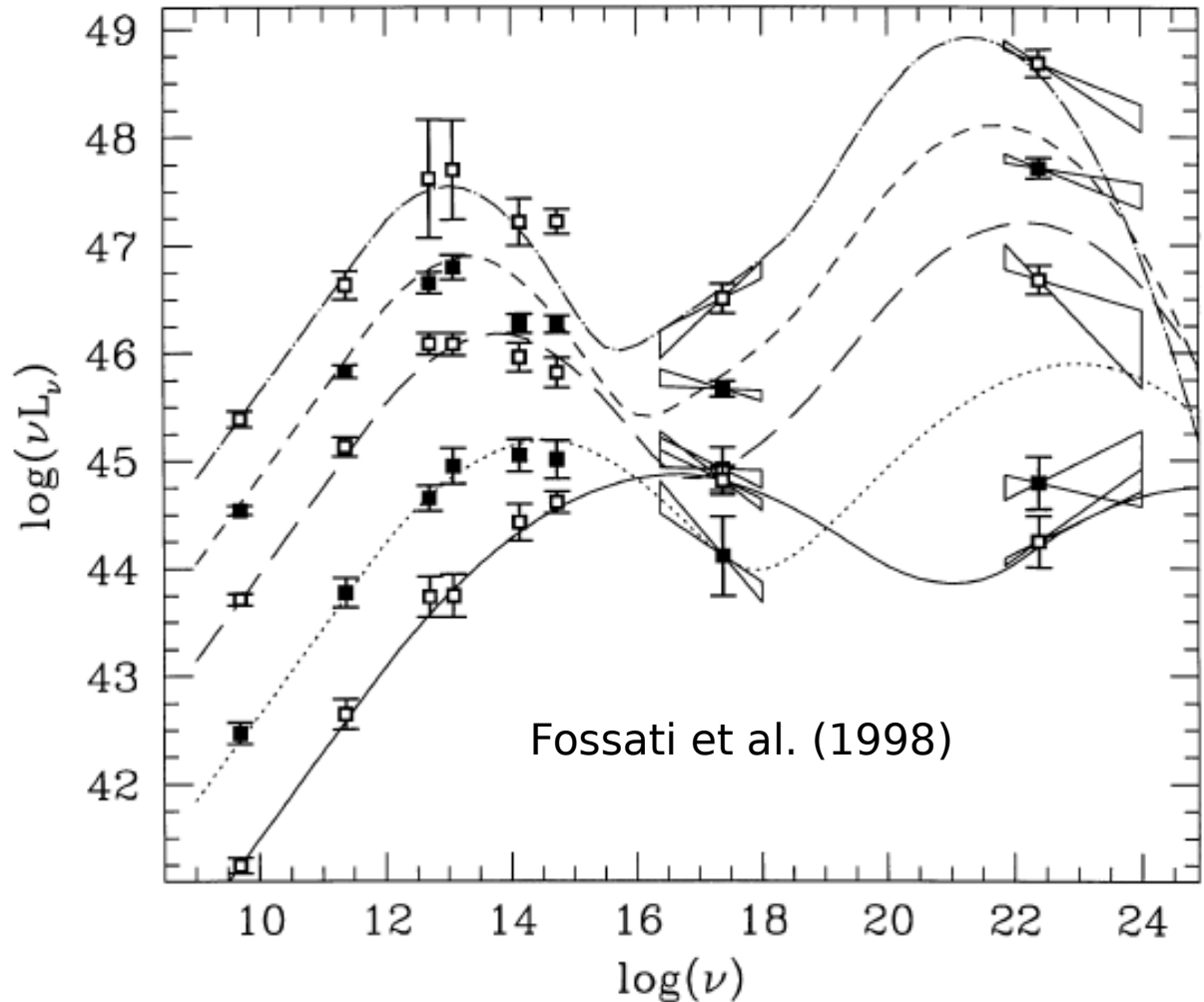
Luminosity vs. Redshift





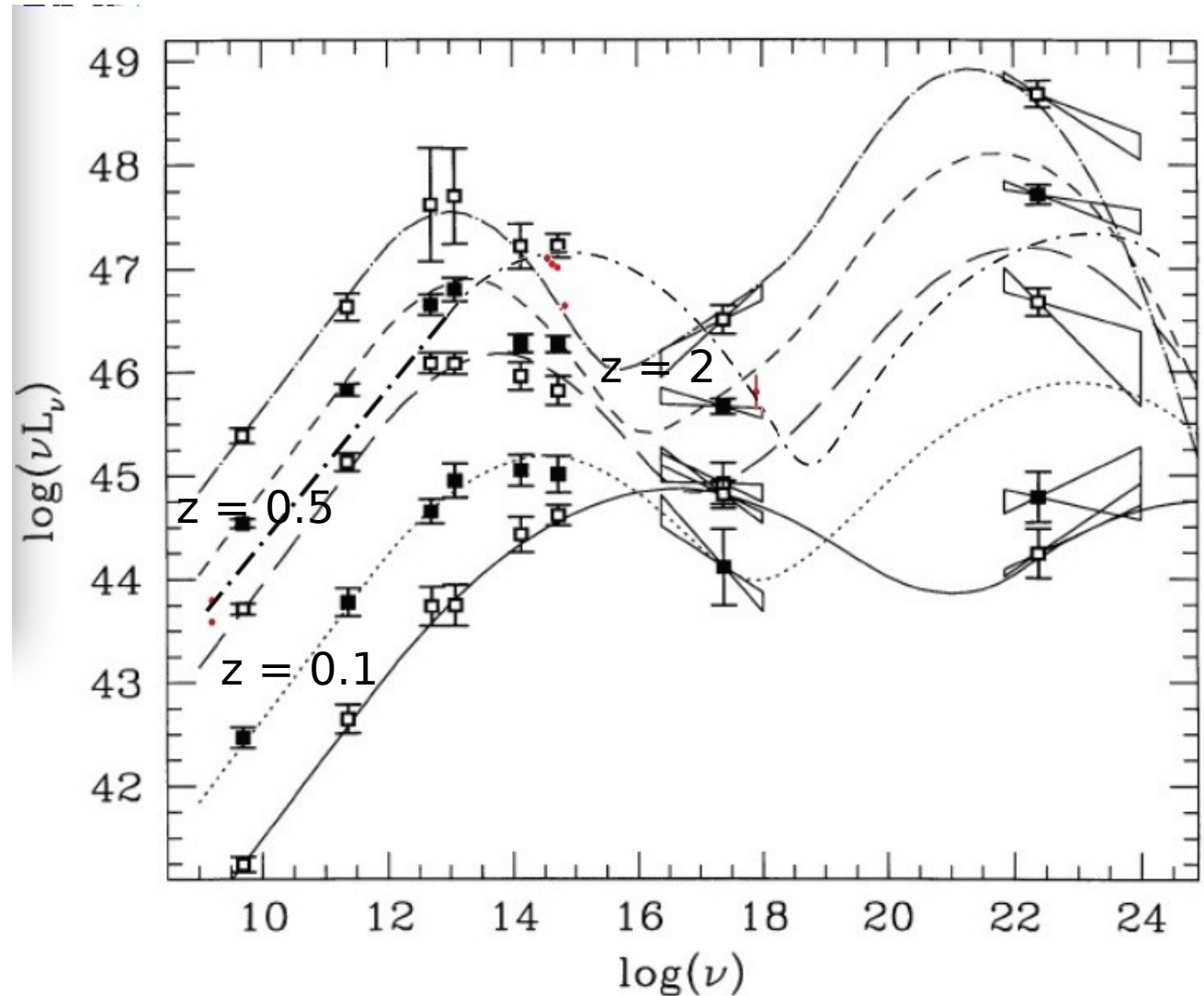
Blazar Sequence

- Searching for the Hertzsprung-Russell Diagram in blazar studies
- Inverse correlation between E_{peak} and luminosity
- Cooling model with external radiation for FSRQs (Ghisellini et al. 1998)
- Selection biases from 2 Jy FSRQs (Wall & Peacock catalog), 1 Jy BL Lac (radio selected), and Einstein Slew Survey (X-ray selected) (Giommi et al. 1999; Padovani et al. 2003, Padovani 2007)



Selection Biases to the Blazar Sequence

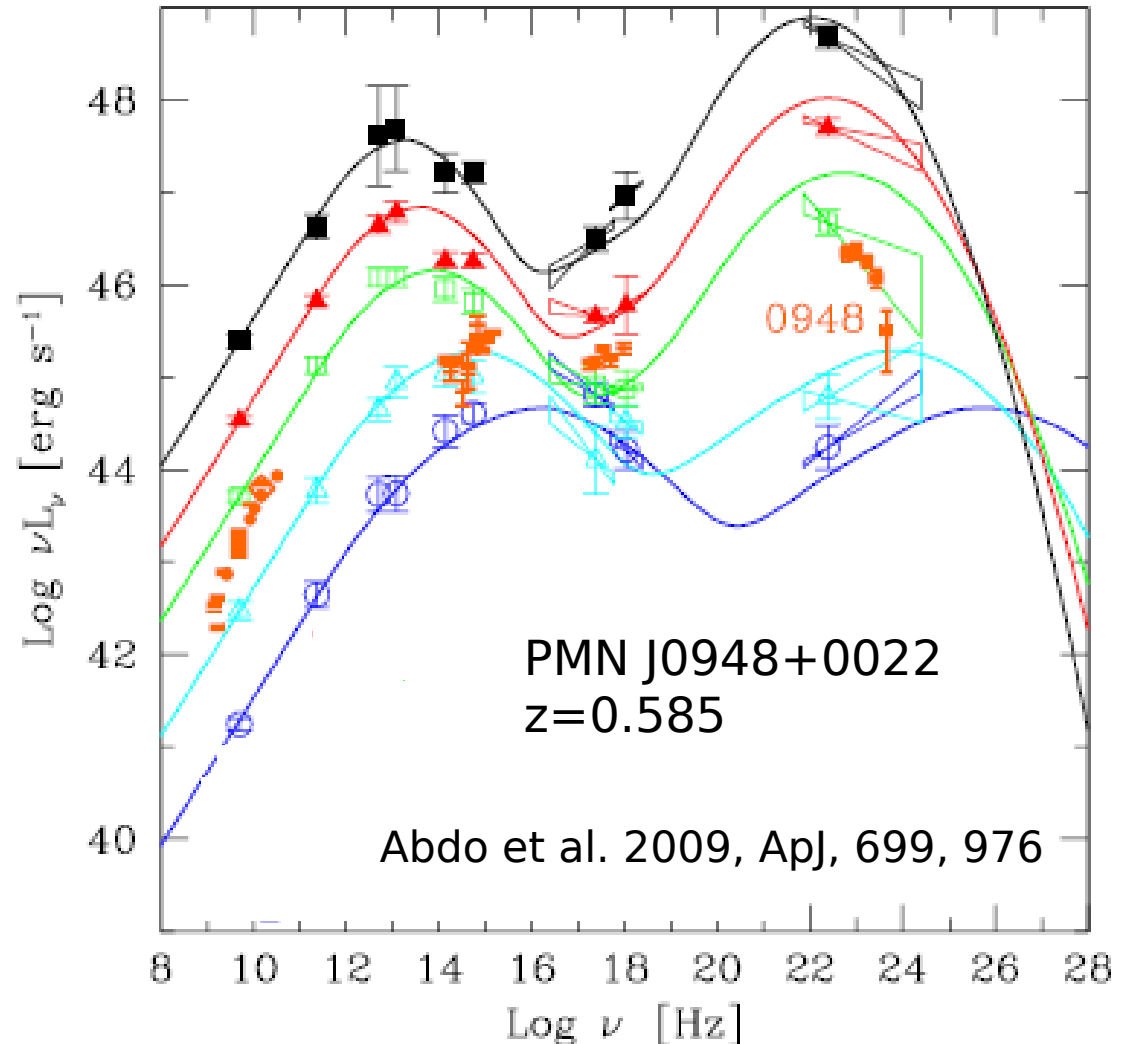
- Increased sensitivity of Fermi to high-peaked low-luminosity BL Lacs (Giommi, private comm.)
- Large number of BL Lacs without redshift: are these high luminosity?
- Outliers



Understanding the Blazar Sequence

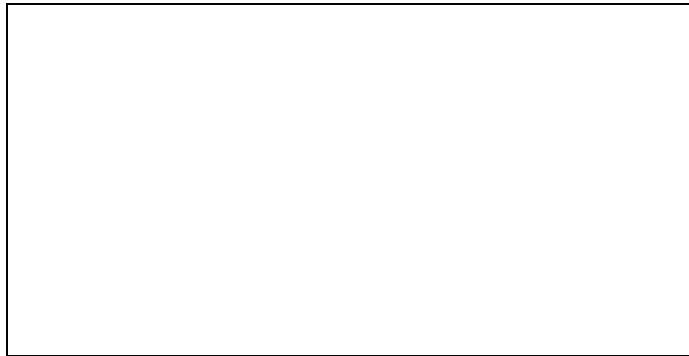
- Origin of the sequence
 - **Galaxy evolution**
 - **Elliptical hosts of blazars**
 - **BZ effect**
 - Evolutionary behavior of FSRQs and BL Lacs
 - **reduction of fuel from surrounding gas and dust**
- (Cavaliere and d'Elia 2002; Böttcher and Dermer 2002)
- In accord with unification of radio galaxies and blazars
 - Where do NLRLSy1s fit?

See Abdo et al. 2009, ApJ, 699, 976

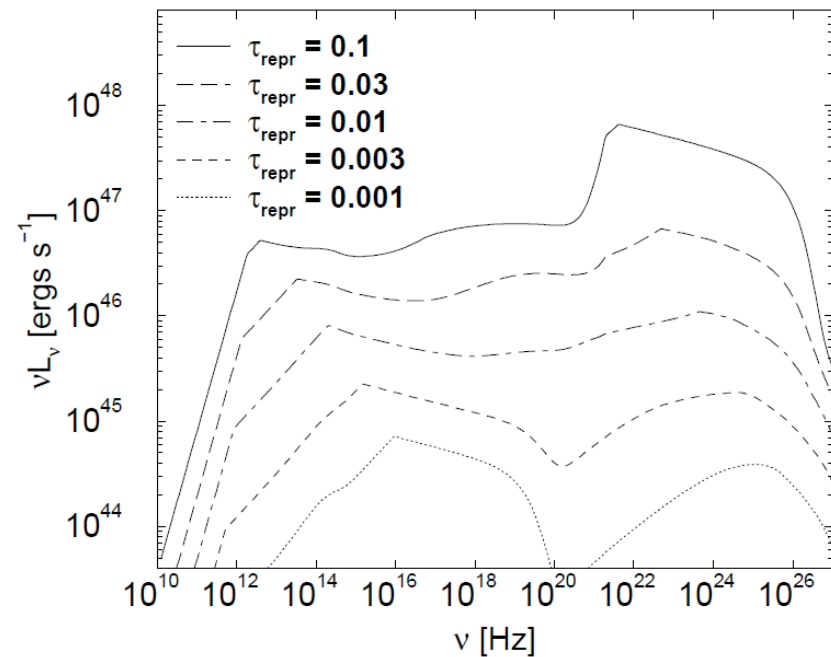


Cooling Model for the Blazar Sequence

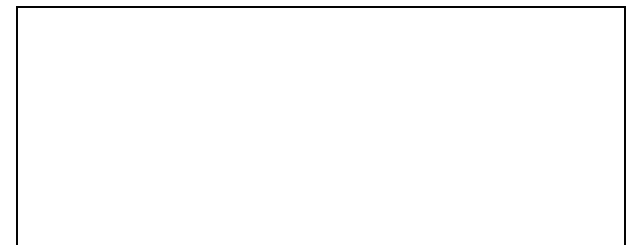
Preliminary: not for distribution



PKS 1510-089
 $z = 0.361$



Preliminary: not for distribution

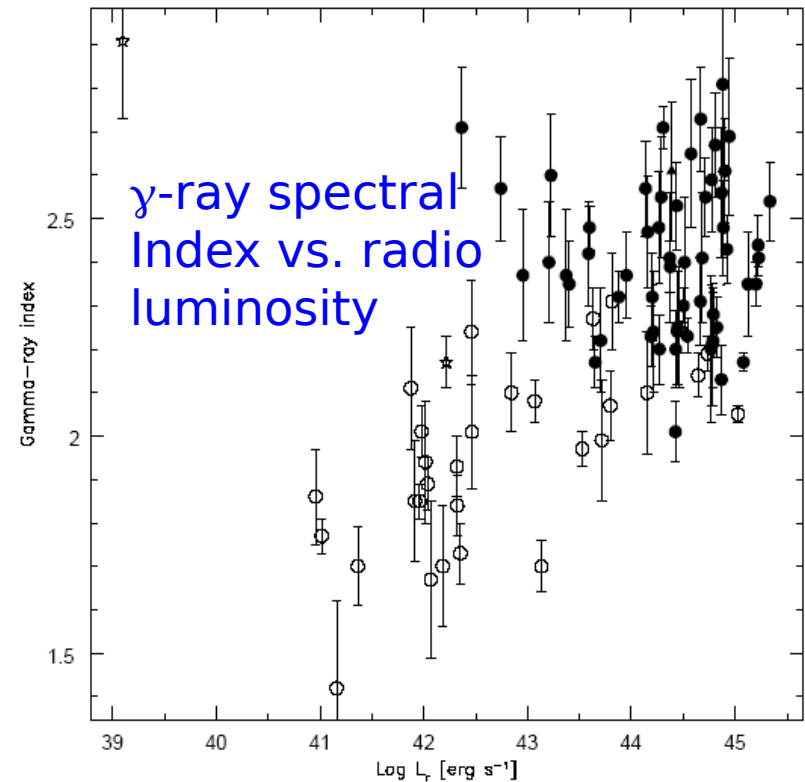
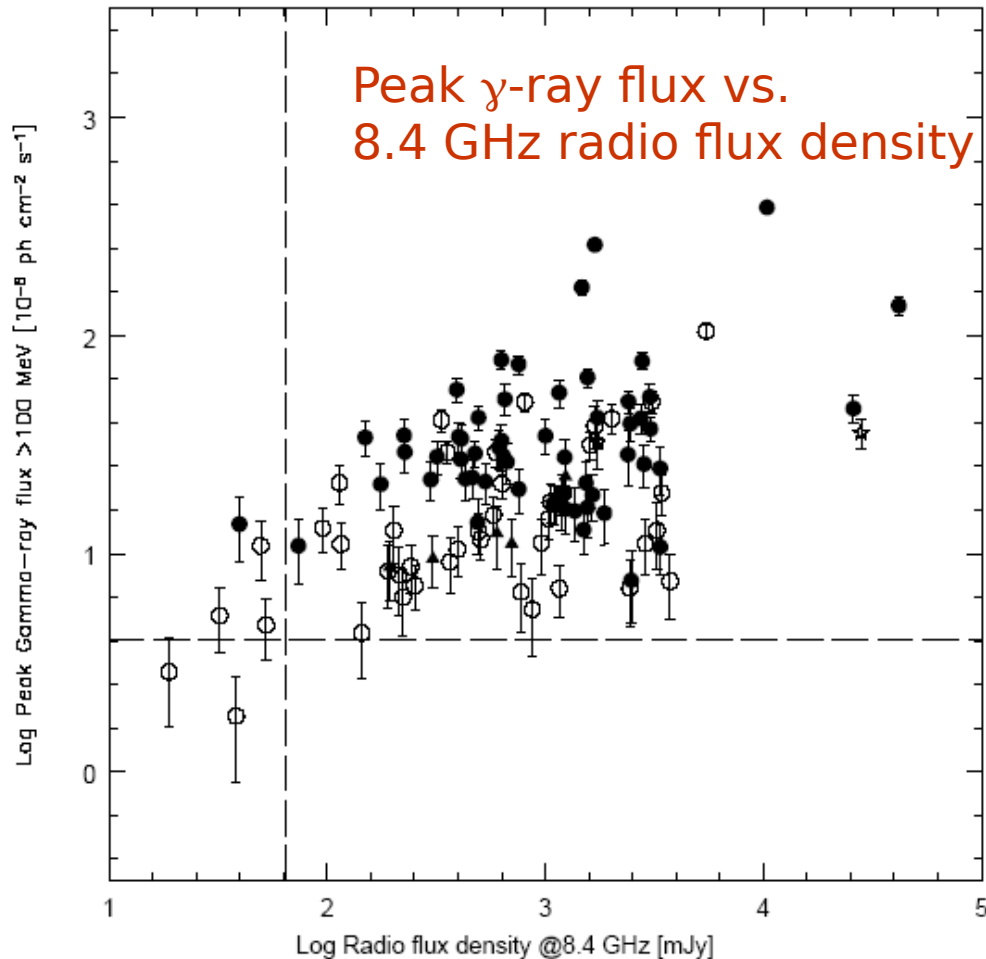


Mrk 421
 $z = 0.031$

- Difficulties of cooling model;
e.g., Begelman, Fabian, & Rees
(2008)

Radio/ γ ray Correlations

- Radio/ γ -ray correlation important in population studies



γ-ray Population Studies

Stecker and Salamon (1996)
assuming radio-γ correlation

Chiang and Mukherjee (1997)

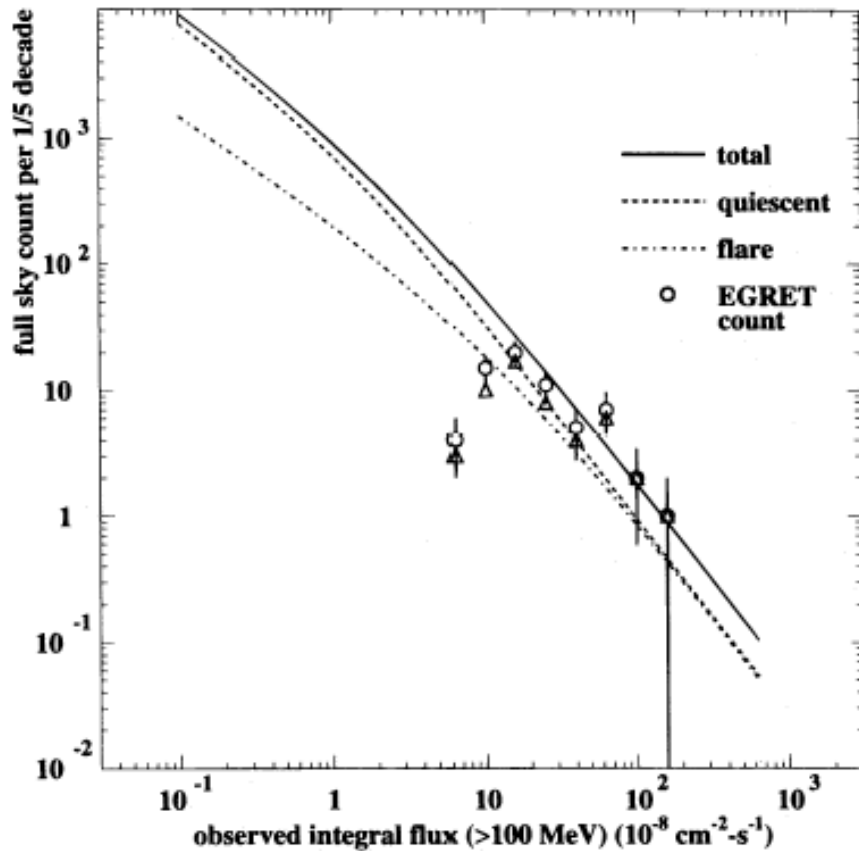
Narumoto and Totani (2005)

RLF

$$\rho_r(P_r, z) = 10^{-8.15} \left\{ \left[\frac{P_r}{P_c(z)} \right]^{0.83} + \left[\frac{P_r}{P_c(z)} \right]^{1.96} \right\}^{-1}$$

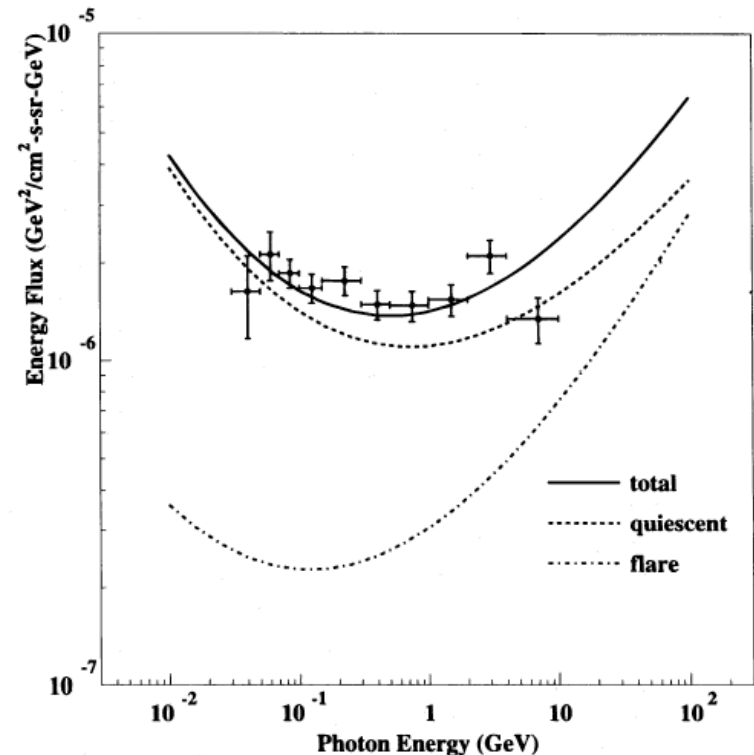
γLF

$$\rho_\gamma(P_{\gamma f}, z) = (1 - \zeta)\eta\rho_r\left(\frac{P_{\gamma f}}{\kappa}, z\right) + \zeta\eta\rho_r\left(\frac{P_{\gamma f}}{A\kappa}, z\right)$$



Dermer

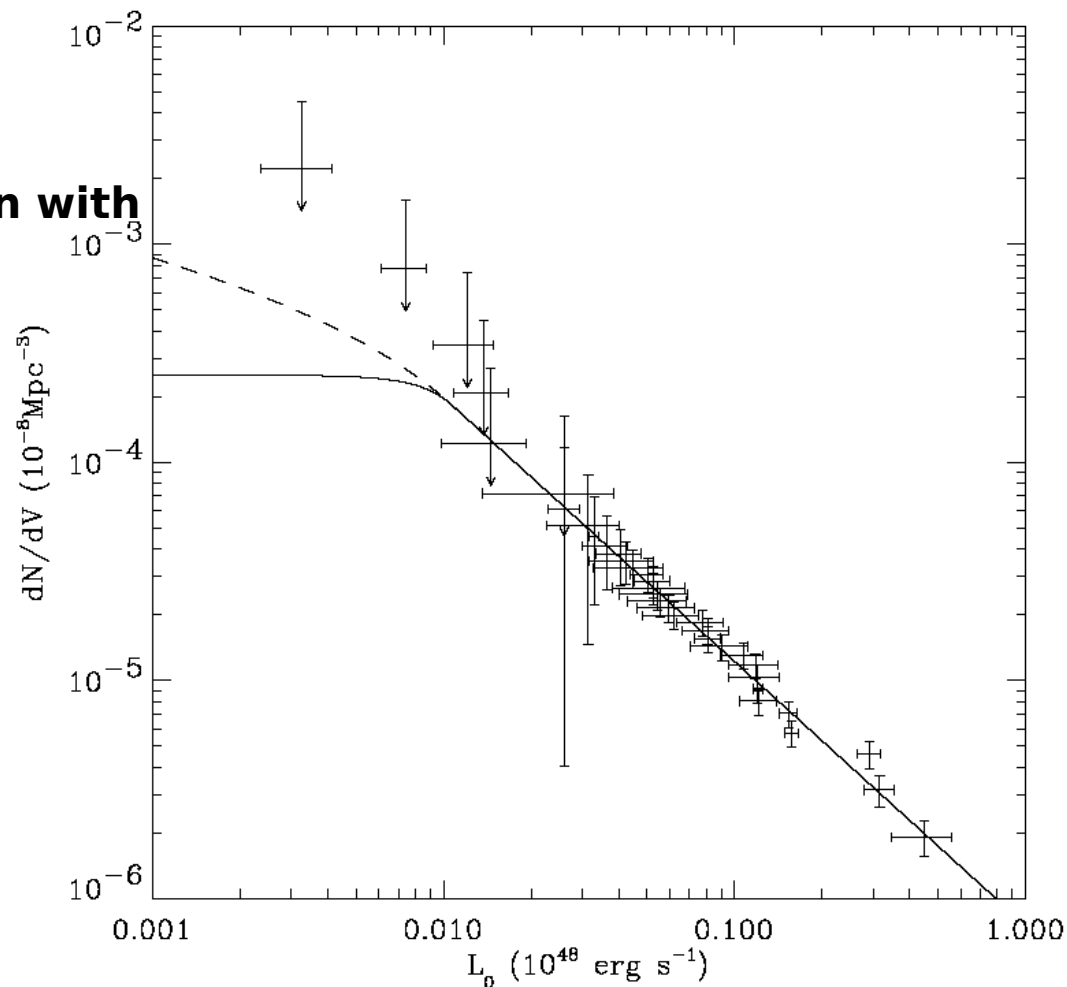
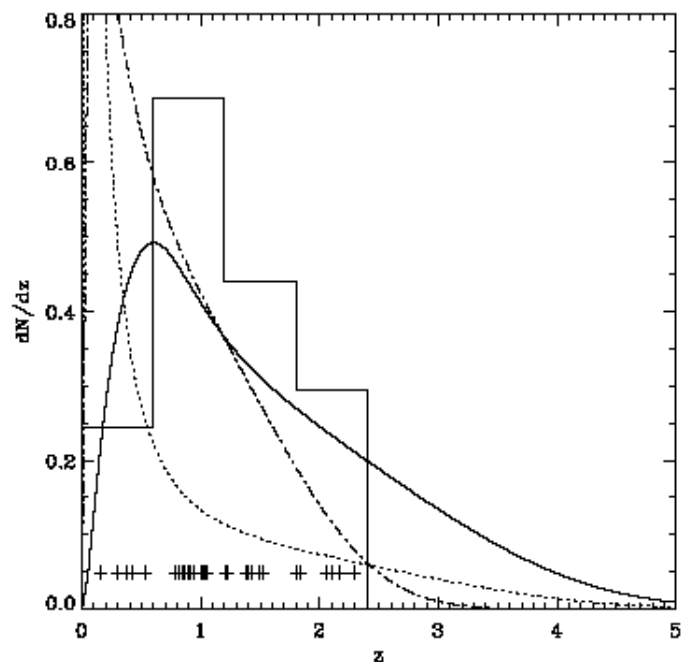
Saas-F



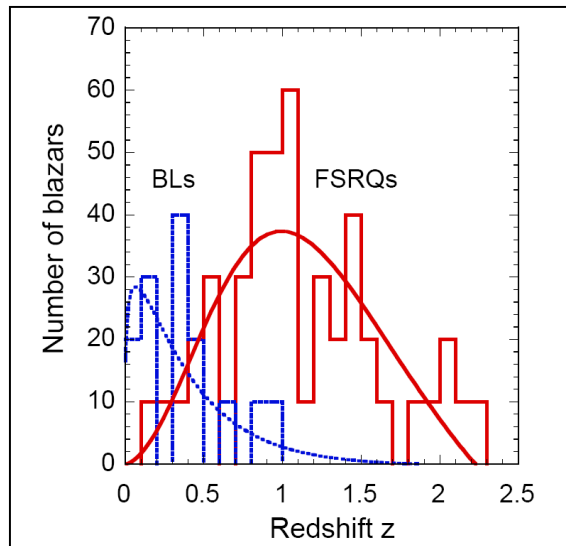
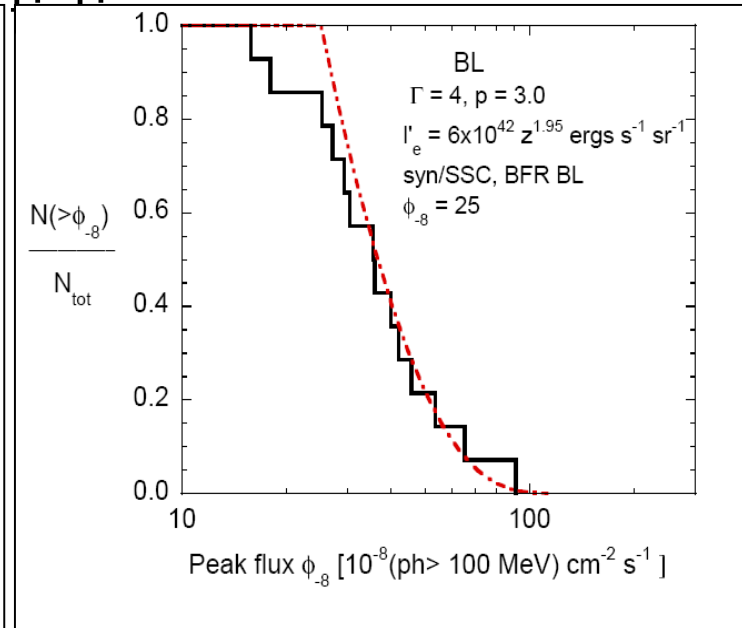
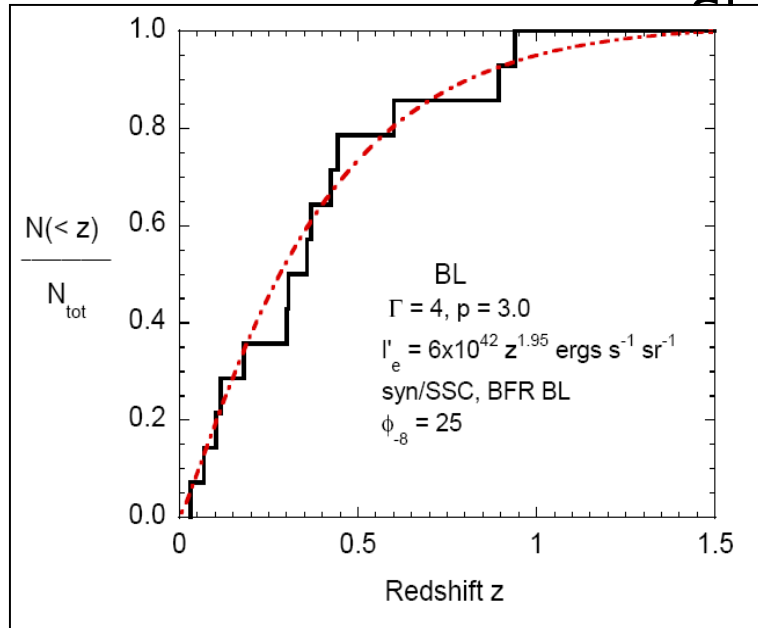
γ -ray Population Studies with Luminosity Function

Chiang et al. (1995)
Giommi and Colafrancesco
(2006)

Requires luminosity evolution with redshift



Physical Model of Blazars for Population



Redshift and Flux Distribution of EGRET blazars, separated into 46 FSRQs and 14 BL Lac Objects (BLs).

Uniform exposure: EGRET all-sky survey:
 Fichtel et al. (1994): 1EG

Fit required positive evolution of FSRQs,
 negative evolution of BL Lacs consistent
 with blazar sequence (Dermer 2007)

Comparison of Predictions for GLAST/Fermi

Other physical models:

Mücke and Pohl (2000)

Predictions naively took

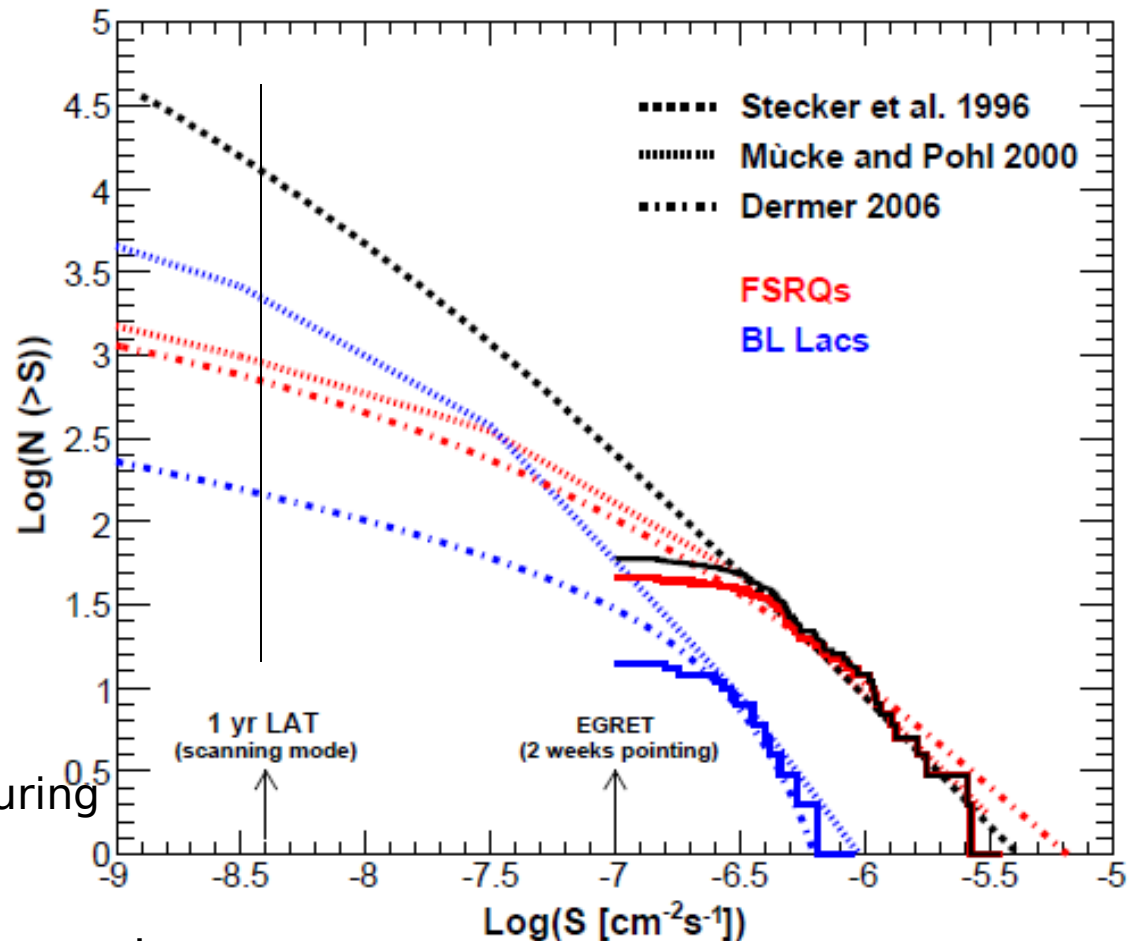
same flux limit for
BL Lacs and FSRQs,
though limiting flux
very

sensitive to spectral
index

Model based on validity
of blazar sequence:

Inoue and Totani (2009)

predict 600-1200 blazars during
first year



⇒ blazar contribution to the
diffuse/unresolved γ -ray background

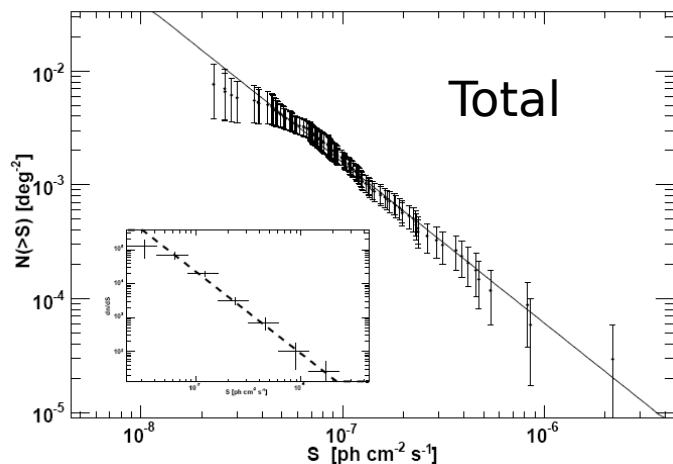
1LAC Highlights

The First Catalog of Active Galactic Nuclei Detected by the *Fermi* Large Area Telescope

- ❑ ~90% success rate in correlating high-latitude bright Fermi sources with AGNs
- ❑ Bright extragalactic γ -ray sky dominated by radio-loud AGNs/blazars
- ❑ Larger fraction of BL Lacs to total than found with EGRET
- ❑ Much harder GeV spectra with BL Lacs ($\Gamma \cong 2.0$) than FSRQs ($\Gamma \cong 2.40$)
- ❑ Mean redshifts of BL Lacs ($z \cong 0.1$) vs. FSRQs ($z \cong 1$)
- ❑ Only ~30% of LBAS detected with EGRET
- ❑ Only weak correlation between peak γ -ray flux and radio flux density
- ❑ V/V_{\max} test reveals strong positive evolution for FSRQs
- ❑ Combined emission between $(7 - 10) \times 10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1}$ make up ~7% of EGRET extragalactic unresolved background

Backup Slides

Log N – Log S and Extragalactic γ -Ray Intensity



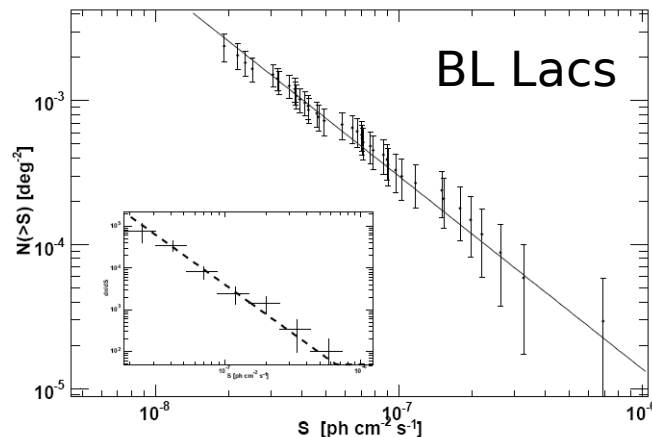
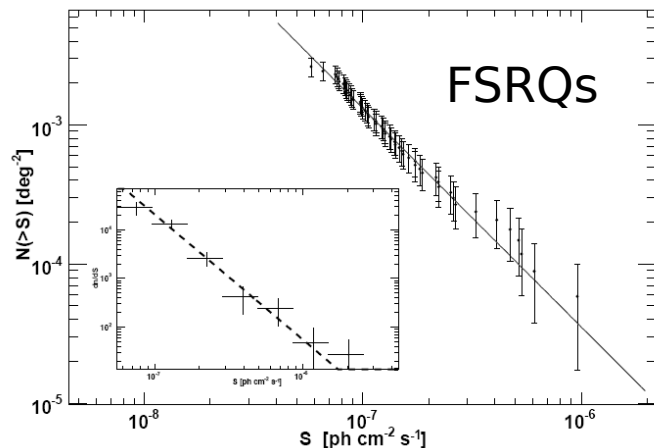
SAMPLE	# Objects	α	A ^a	EDB fraction ^b
All ^c	121	2.59 ± 0.12	2.62 ± 0.24	7.2 %
Blazars	106	2.50 ± 0.12	$2.24 \pm 0.22 (\pm 0.24)$	6.1 %
FSRQs	57	2.60 ± 0.14	$2.15 \pm 0.28 (\pm 0.32)$	3.1 % ^d
BL Lacs	42	2.34 ± 0.15	$0.41 \pm 0.06 (\pm 0.06)$	1.0 %

^aIn units of $10^4 \text{ cm}^2 \text{ s deg}^{-2}$.

^bFraction of the EGRET diffuse extragalactic background (Sreekumar et al. 1998) resolved into sources by LAT for $4 \times 10^{-8} < F_{100} < 10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1}$.

^cIncludes all sources except 7 pulsars and 4 anti-associated objects.

^dThe lower limit of integration in Eq. 7 has been set to $6 \times 10^{-8} \text{ ph cm}^{-2} \text{ s}^{-1}$.



Luminosity Function

□ Redshift-dependent luminosity function

